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Variability of silver fir (Abies alba Mill.) cones – variability of cone parameters

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Abstract. This study aimed at determining the shape of closed silver fir cones from the Jawor Forest District (Wroclaw), based purely on measurements of their length and thickness. Using these two parameters, the most accurate estimations were achieved with a fourth-degree polynomial fitting function. We then calculated the cones' surface area and volume in three different ways: 1) Using the fourth-degree polynomial shape estimation, 2) Introducing indicators of compliance (k1, k2, k3) to calculate the volume and then comparing it to its actual value as measured in a pitcher filled with water, 3) Comparing the surface area of the cones as calculated with the polynomial function to the value obtained from ratios of indicators of compliance (ratios k4 and k5).We found that the calculated surface area and volume were substantially higher than the corresponding measured values. Test values of cone volume and surface area as calculated by our model were 8% and 5% lower, respectively, compared to direct measurements. We also determined the fir cones apparent density to be 0.8 g·cm-3on average. The gathered data on cone surface area, volume and bulk density is a valuable tool for optimizing the thermal peeling process in mill cabinets to acquire high quality seeds.

Keywords: cone, scales, area, volume, shape

1. Introduction

Silver fir (*Abies alba* Mill.) grows in southern and middle Poland, reaching its northern limit of distribution. This species is most numerous in Karpaty Mountains on a height of 500–1100 m a.s.l., in Sudetes, Świętokrzyskie Mountains and on Roztocze (Gunia, Kowalski 1968; Wilczkiewicz 1976; Gunia 1986; Sabor et al. 1999; Barzdajn 2009; Bednarek 2002; Sugiero 2005; Szeligowski et al. 2011; Bis, Dobrowolska 2012).

When grown in canopy, the Silver fir bears seeds at the age of 70 years, and in open spaces – at the age of around 30 years (Załęski 1995). This species bears seeds every 3–4 years. Ripe cones of Silver fir are grey-brown, have a length of 10–17 cm and a thickness 3–5 cm (Tyszkiewicz 1949; Boratyński 1983; Suszka 1983; Schütt 1991; Tracz, Barzdajn 2007; Jaworski, Paluch 2007). Authors Gudeski (1966), Kočiová (1974), Nanu (1977) or Ballianand Čabaravdić (2005) have written about the parameters of cones and seeds of fir from other regions. The fir's cones grow vertically on branches, and after ripening, they fall apart into scales and seeds. The scales and seeds fall down on soil and the axis remains on the tree.

Cones are collected from standing trees by hand before they fully ripen. Obtaining the fir's seeds from cones does not involve using high temperatures and special peeling devices like in the case of common spruce (*Picea abies* (L.) H. Karst), Scots pine (*Pinus sylvestris* L.) or European larch (*Larix decidua* Mill.). According to the instructions of collection and storage of gene resources (Forest Gene Bank in Kostrzyca 2007), the cones should be placed in boxes with perforated bottoms in a ventilated hall with a temperature of 20°C. Cones, during storage are raked, and they dry and fall apart partially into scales, seeds and axes. Finally, the material is subjected to crushing and then separation in a seed drum sieve. The process of fir's cones peeling can be mechanized, but in order to do so, besides acquaintance of temperature conditions, acquaintance of the cones' structure is needed.

The authors, in a few publications, have described the external parameters of cones and scales, the mass of the seeds or their wings, their mutual dependence (Politi et al. 2011; Jaworski, Paluch 2007; Illoul-Hachi et al. 2015), and also the influence of environment on population or hybrids (Kobliha et al. 2014).In the publications, the parameters of cones of other species were

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described in detail, inter alia, common spruce (Kulej, Skrzyszewska 1996), along with showing the dependence between their dimensions (Barzdajn 1996) and the environment from which the material came (Illoul-Hachi et al. 2015). Buraczyk (2009), in studies on cones of common spruce, drew attention to the influence of cones' size and scales' location on the speed of opening of the cones and the seed's release.

The aim of this research was to make an attempt to establish the shape of the cones and to elaborate the most accurate model for the calculation of surface and volume of closed cones of Silver fir. The knowledge of the described parameters can help in the optimization of conditions for peeling realization, while taking into account the biological characteristics of the seeds.

2. Material and methods

In this research, we used closed cones of Silver fir that were collected in the economic seed stands in Jawor Forest Inspectorate (Regional Directorate of State Forests in Wrocław) from 751 regions of the origin.

For each of the 30 randomly chosen cones (Fig. 1), we measured length (h), thickness – the largest diameter of cone (d), mass (m) and number of scales (n). The average humidity of cones was evaluated.

Figure 1. View of the investigated silver fir cones (fot. M. Aniszewska)

A slide calliper was used for the measurement of length and thickness of closed cones and a laboratory scale WPS 600 was used for the measurement of mass. The accuracy of length and thickness measurement amounted 0.1 cm, and the accuracy of mass measurement was 0.1 g.

On the base of length measurement and diameter additionally measured sequentially every 5 mm, calculated was surface area of each cone. Closed cones were treated as having a lathed shape. The generatrix of the external surface was outlined. The distance of location of cross-section from the base of the cone was adopted as a zero point of the system of coordinates (Aniszewska 2001).The coordinates of location of cross-section and the radius designed for each cone were the base for approximation of the equation, defying the generatrix of the cone's external surface.

The shape function $y = f(x)$ was constant and non-negative on the whole length of the cone (h), therefore the surface area (S_{obl}) could be calculated with the use of formula (1):

$$S_{obl} = 2 \cdot \pi \int_a^b y \, dL = 2 \cdot \pi \int_0^h y \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \, dx \qquad (1)$$

where:

dL – differentia of the shape function

By taking into consideration the fact that the area of the base of this entity was small, we assumed that the side surface was equal to the cone's external surface.

Volume of the cone (V_{obl}) was designed using the formula (2):

$$V_{obl} = \pi \int_0^h y^2 dx \qquad (2)$$

The external surface and volume of the examined cones was also calculated by using the commonly known formulas for side area and volume of cylinder (S_w, V_w) and cone (S_s, V_s), where *d* is the diameter of cone at the thickest point, *h* is the length of cone and *l*- is the generatrix of cone (Fig. 2).

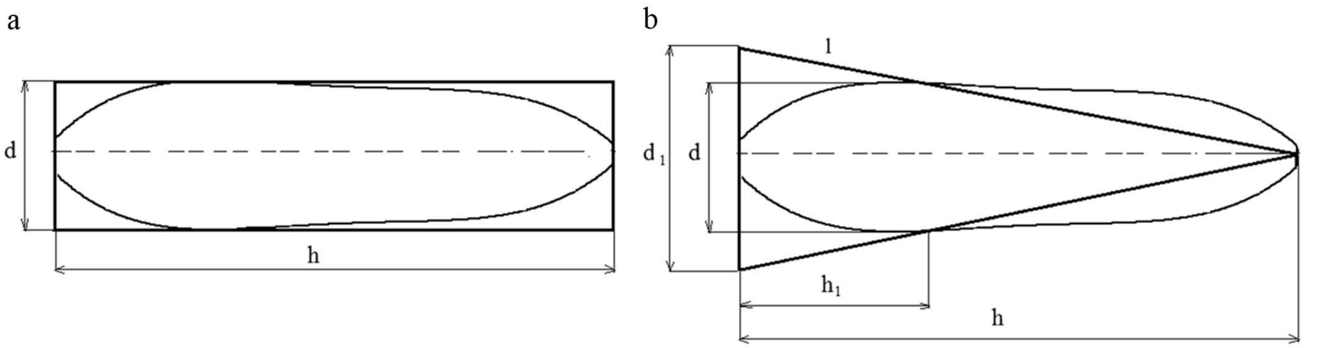

Figure 2. Geometric models mapping the shape of silver fir cones: a – cylinder, b – cone

In order to calculate the examined values more precisely, it was proposed to introduce a coefficient α to the formulas for area surface S_s (3) and volume V_s (5) of the cone. Coefficient α was equal to ratio of h_1 and h (Aniszewska 2001). Symbol h_1 is the distance from the cone's base to the location of cross-section of its maximum diameter (Table 1). The generatrix of cone-l is a straight line drawn from the apex through point d defying the maximum diameter, and d_1–the diameter of the base of the cone (Fig. 2b).

$$S_S = \pi \cdot \frac{d_1}{2} \cdot \sqrt{(\frac{d_1}{2})^2 + h^2} \quad (3)$$

where:
S_S – surface area calculated from a cone,
d_1, h – as given in Figure 2

The geometrical dependence indicates that:

$$r_1 = h\frac{r}{h - h_1} = \frac{r}{1 - \alpha} \quad (4)$$

where:
r_1 – radius of the cone base,
r – cone's radius.

$$V_s = \frac{1}{3}\pi \cdot (\frac{d_1}{2})^2 \cdot h \quad (5)$$

where:
V_S – volume of the cone calculated from a cone.

Additionally, we measured the cone's actual volume (V_{rz}). For measurement, a measuring cylinder filled with water was used. The volume of the supplanted liquid was adopted as the cone's volume. The measurements were made with accuracy to 1000 mm^3. The density of cones was calculated as a quotient of mass and actual volume.

For comparison of the calculated volume values, indicators of compliance were introduced according to models with actual volume: $k_1 = V_{obl} / V_{rz}$, $k_2 = V_w / V_{rz}$, $k_3 = V_s / V_{rz}$, $k_4 = S_{obl} / S_w$, $k_5 = S_{obl} / S_s$.

Descriptive statistics (Statistica 2011) were made for external parameters. The mean value, length of half-interval confidence for mean and minimum and maximum for standard deviation were defined. The average surface area and volume were compared with the F- test of variance analysis. Homogeneity of variance (Levene's test) and correspondence with normal distribution was also tested. For testing the normality of distribution of dependent variable, Shapiro-Wilk test was used. All analysis were made on significance level $\alpha = 0.05$.

3. Research results

3.1. Characteristic parameters of cones

The length (h) and thickness values *(d)* of examined cones of Silver fir are given in Table 1. The length of cones ranged from 12.4 to 19.7, having an average of 16.43 (±0.67) cm. The thickness ranged from 3.1 to 4.2, with an average of 3.75 (±0.42) cm. The number of scales in a cone amounted from 125 to 219, average being 185 (±7.60). A significant dependence between thickness and length of cones, number of scales (n) and those two characteristics was showed. Equations of linear correlation and coefficients of determination are given below.

$$d = 0.132\ h + 1.571 \qquad R^2 = 0.650 \quad (6)$$

Increase of length of cone by 1 cm caused an increase in its volume by 1.3 mm.

$$n = 9.732\ h + 25.06 \qquad R^2 = 0.523 \quad (7)$$

Equation (7) indicated that with each centimetre there were 10 more scales.

The mass of closed, fresh cones amounted to an average of 105.91 g (±8.85) and ranged from 48 to 142 g (Table 1). Average humidity of Silver fir cone's right after harvesting amounted to an average of 110%.

Density for the examined part of cones amounted from 0.68 to 0.90 g·cm^{-3}, having an average of 0.81g·cm^{-3}(±0.02).

3.2. Surface and volume of closed cones

After many trials, the fourth-degree polynomial was chosen as the best representative of the shape of cones. The determination coefficient R^2 obtained ranged from 0.949 to

Table 1. Characteristic parameters of silver fir cones

No. of cone	Lenght	Distance from the base	Coefficient	Thickness	Number of scales	Weight	Actual volume
	h	h_1	$\alpha = h_1/h$	d	n	m	V_{rz}
	cm	cm	-	cm	szt.	g	cm^3
1	14.4	6.0	0.42	3.5	187	84.3	100
2	17.6	7.0	0.40	3.8	184	109.0	136

No. of cone	Lenght	Distance from the base	Coefficient	Thickness	Number of scales	Weight	Actual volume
	h	h_1	$\alpha=h_1/h$	d	n	m	V_{rz}
	cm	cm	-	cm	szt.	g	cm^3
3	15.8	6.5	0.41	3.4	188	81.6	100
4	19.7	6.5	0.33	4.0	216	141.8	180
5	17.2	5.5	0.32	3.8	199	110.9	150
6	15.7	5.0	0.32	3.5	182	97.6	115
7	12.5	5.0	0.40	3.5	157	76.7	88
8	17.0	3.5	0.21	4.2	202	122.7	160
9	14.4	3.5	0.24	3.4	155	65.6	80
10	13.7	3.5	0.26	3.20	162	73.1	85
11	16.8	4.0	0.24	4.10	190	129.3	160
12	18.2	7.0	0.38	3.90	192	110.1	145
13	18.5	4.0	0.22	3.90	202	125.0	150
14	17.5	4.0	0.23	4.10	197	132.1	170
15	17.2	6.0	0.35	3.90	186	100.6	148
16	14.1	4.0	0.28	3.65	152	90.5	110
17	16.5	5.0	0.30	3.60	196	101.3	130
18	17.8	5.0	0.28	4.2	198	136.2	160
19	18.0	4.0	0.22	4.2	197	136.3	160
20	17.5	4.5	0.26	3.8	206	119.7	160
21	16.6	4.5	0.27	4.0	179	135.5	150
22	17.0	5.0	0.29	3.8	177	105.4	135
23	17.1	7.0	0.41	4.0	192	115.2	145
24	15.2	6.0	0.39	3.5	176	92.0	110
25	17.0	5.0	0.29	4.0	174	111.4	140
26	12.4	4.0	0.32	3.1	125	48.2	60
27	14.7	4.5	0.31	3.5	171	80.8	90
28	16.8	5.0	0.30	3.7	208	120.6	140
29	17.2	3.5	0.20	3.8	179	94.0	120
30	18.7	4.0	0.21	3.9	219	129.7	182
Mean	16.43	4.93	0.30	3.75	184.93	105.91	131.97
Standard deviation	1.79	1.12	0.07	0.29	20.36	23.70	31.67
Min	12.4	7.0	0.20	3.10	125	48.2	60
Max	19.7	3.5	0.42	4.20	219	141.8	182

α, h_1, h – as in Figure 2

0.996, with an average of 0.980. The general formula for the shape of generatrix of cones was as follows:

$$y=Ax^4+Bx^3+Cx^2+Dx+E, \tag{8}$$

gdzie $x \in (0, h)$.

The mean value, standard deviation and minimum and maximum values of coefficients from A to E are given in Table 2. The exemplary course of changes of generatrix for cones is given on Figure 3.

The designed equations of generatrix of individual cones allowed for surface area S_{obl} and volume calculation V_{obl} (Table 3).

Due to a large variability of coefficients A, B, C and E of polynomial for individual cones, despite significant dependence on length (equation 9–12) and thickness, there is no practical possibility of using this equation for the calculation of volume and surface area of any cone of Silver fir when only its basic parameters (d and h) are known.

$$A= 5\times10^{-9}h - 1\times10^{-6} \qquad R^2=0.718 \tag{9}$$

$$B= 1\times10^{-6}h + 3\times10^{-4} \qquad R^2=0.677 \tag{10}$$

$$C=7\times10^{-5}h - 0.026 \qquad R^2=0.410 \tag{11}$$

$$E= 0.044h - 1.366 \qquad R^2=0.423 \tag{12}$$

For coefficient D, no significant dependence on length or thickness of cones was stated.

Values of surface area of cone (S_{obl}), calculated from formula 1, amounted from 87.30 to 261.30 cm^2, with an average of 156.98 (±14.11) cm^2 , and values of volume (V_{obl}), according to the formula 2, from 61.22 to 250.23 cm^3, with an average of 144.01 (±17.13) cm^3 (Table 3).

The values of surface area of cone (S_w) calculated from computational model of cylinder ranged from 121.05 to 247.56 cm^2, with an average of 194.91 cm^2 (±12.51) and values of volume (V_w) from 93.82 to 248.96 cm^3, having an average 185.05 cm^3 (±16.38) (Table 3).

Values of α and h_1 coefficients for individual cones, used in the calculation of surface area S_s and volume V_s of cone, are given in Table 1. On an average, the coefficient α amounted to 0.03 (±0.03) and h_1 was equal to 4.93 (±0.42).

Formulas basis which the values of volume and surface area were calculated according to the cone model (given in Table 3), including α value, have been given in equations13 and 14. The given constants have been taken from equations 3–5.

$$V_s = 0.534 \cdot d^2 \cdot h \tag{13}$$

$$S_s = 1.602 \cdot d \cdot \sqrt{d^2 + 1.96 \cdot h^2} \tag{14}$$

The surface area of cone (S_s) amounted from 87.78 to 178.58 cm^2, having an average of 140.99 cm^2 (±9.01) and volume (V_s) from 63.79 to 169.27 cm^3, on an average 125.82 cm^3 (±11.13) cm^3 (Table 3).

The results of actual volume (V_{rz}) are given in Table 1. The average actual volume amounted to from 60 to 182 cm^3, with an average 131.97 cm^3 (±11.84). The dependence of actual volume was calculated on length and thickness of cones (15 and 16, respectively). The increase in length by 1 cm

Table 2. Statistical values of coefficients $A \div E$ form of the equation

Parameter	*A*	*B*	*C*	*D*	*E*
Mean	–0.00000038	0.0001245	–0.014904	0.752157	5.9349
Standard deviation	0.00000012	0.0000254	0.001875	0.062385	1.2206
Minimum	–0.00000070	0.0000850	–0.019570	0.602319	3.6540
Maximum	–0.00000020	0.0001810	–0.011298	0.882000	8.6000

a

b

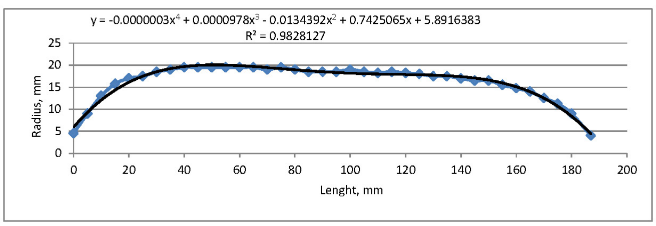

Figure 3. Cone silver fir: a – general view, b – cone outline data visualization

caused the increase of actual volume by almost 16 cm³, and in case of thickness, by around 97 cm³.

$$V_{rz} = 16.2 \cdot h - 133.5 \qquad R^2=0.829 \tag{15}$$

$$V_{rz} = 97.5 \cdot d - 233.9 \qquad R^2=0.817 \tag{16}$$

The values of surface area and volume calculated in three ways were compared with actual values. The average value of k_1 indicator, defying the relation of calculated volume V_{obl} to the measured volume V_{rz} amounted to 1.08 (±0.07). Due to high compliance of the volume calculated (V_{obl}) according to the function of fourth-degree polynomial with value measured for cone (V_{rz}) allowed us to state that the surface S_{obl} *also* calculated with the use of this method is a good approximation of the actual value.

Values of examined factors describing relations of examined indicators:k_1, k_2, k_3, k_4 and$k_5$are given in Table 3.

Value of indicatork_2, which is a ratio of volume calculated from cylinder model (V_w) to measured volume (V_{rz}), ranged from 1.23 to 1.63, on an average 1.41 (±0.04). It was much higher than $k_1$value, which proves that that there are significant differences between values calculated from cylinder model and measured values.

In order to use the cylinder model for calculation of actual volume (V_{wf}), the obtained values should be multiplied by 0.709 (equation 17), and for the calculation of surface area (S_{wf}),the values should be multiplied by 0.810, which indicates S_w and S_{obl} (k_4) dependence .

$$V_{wf} = V_w/k_2 = V_w/1.41 = V_w \cdot 0.709 \tag{17}$$

Table 3. Surface area and volume, and compliance rates for the tested silver fir cones

No. of cone	Surface area	Volume	Surface area	Volume	Surface area	Volume	Compliancerates				
	S_{obl}	V_{obl}	S_w	V_w	S_s	V_s	k_1	k_2	k_3	k_4	k_5
	cm²	cm³	cm²	cm³	cm²	cm³	-	-	-	-	-
1	122.56	91.66	155.97	134.52	112.97	91.46	0.92	1.35	0.91	0.79	1.08
2	168.91	137.42	208.77	197.28	150.79	134.14	1.01	1.45	0.99	0.81	1.12
3	141.98	106.41	168.77	143.45	121.90	97.53	1.06	1.43	0.98	0.84	1.16
4	261.30	250.23	247.56	247.57	178.58	168.32	1.39	1.38	0.94	1.06	1.46
5	171.49	140.44	202.75	190.08	146.49	129.24	0.94	1.27	0.86	0.85	1.17
6	134.66	101.17	172.08	150.57	124.41	102.37	0.88	1.31	0.89	0.78	1.08
7	111.59	84.23	136.99	119.18	99.70	81.03	0.96	1.35	0.92	0.81	1.12
8	181.47	162.89	222.03	230.36	160.89	156.62	1.02	1.44	0.98	0.82	1.13
9	114.80	80.45	153.39	130.38	111.06	88.64	1.01	1.63	1.11	0.75	1.03
10	124.53	93.04	137.73	110.18	99.68	74.91	1.09	1.30	0.88	0.90	1.25
11	193.33	203.28	216.52	221.93	156.90	150.90	1.27	1.39	0.94	0.89	1.23
12	191.33	196.84	222.99	217.42	161.05	147.82	1.36	1.50	1.02	0.86	1.19
13	189.08	159.52	226.67	221.00	163.64	150.26	1.06	1.47	1.00	0.83	1.16
14	149.40	155.77	224.77	230.38	162.71	156.64	0.92	1.36	0.92	0.66	0.92
15	188.14	173.41	210.74	205.47	152.41	139.70	1.17	1.39	0.94	0.89	1.23
16	135.55	108.42	162.14	147.95	117.70	100.60	0.99	1.35	0.91	0.84	1.15
17	198.22	197.77	186.05	167.44	134.43	113.84	1.52	1.29	0.88	1.07	1.47
18	185.87	175.48	231.68	240.37	167.68	163.43	1.10	1.50	1.02	0.80	1.11
19	143.63	140.93	237.11	248.96	171.62	169.27	0.88	1.56	1.06	0.61	0.84

No. of cone	Surface area	Volume	Surface area	Volume	Surface area	Volume	Compliancerates				
	S_{obl}	V_{obl}	S_w	V_w	S_s	V_s	k_1	k_2	k_3	k_4	k_5
	cm^2	cm^3	cm^2	cm^3	cm^2	cm^3	-	-	-	-	-
20	159.88	131.51	209.04	198.58	151.01	135.02	0.82	1.24	0.84	0.76	1.06
21	202.95	223.18	208.10	208.10	150.76	141.49	1.49	1.39	0.94	0.98	1.35
22	180.11	170.80	202.95	192.80	146.72	131.09	1.27	1.43	0.97	0.89	1.23
23	159.19	161.83	215.14	215.14	155.71	146.27	1.12	1.48	1.01	0.74	1.02
24	150.80	135.62	164.96	142.28	119.30	96.74	1.23	1.29	0.88	0.91	1.26
25	178.29	167.16	210.96	208.32	152.66	141.64	1.19	1.49	1.01	0.85	1.17
26	93.62	61.22	121.05	93.82	87.78	63.79	1.02	1.56	1.06	0.77	1.07
27	117.20	79.57	159.76	137.79	115.64	93.69	0.88	1.53	1.04	0.73	1.01
28	152.86	131.86	195.75	181.07	141.45	123.11	0.94	1.29	0.88	0.78	1.08
29	87.30	124.82	205.45	195.18	148.49	132.71	1.04	1.63	1.11	0.42	0.59
30	119.48	173.21	229.61	223.87	165.72	152.21	0.95	1.23	0.84	0.52	0.72
Mean	156.98	144.01	194.91	185.05	140.99	125.82	1.08	1.41	0.96	0.81	1.12
Standard deviation	37.78	45.88	33.49	43.86	24.12	29.82	0.19	0.11	0.08	0.13	0.19
Min	87.30	61.22	121.05	93.82	87.78	63.79	0.82	1.23	0.84	0.42	0.59
Max	261.30	250.23	247.56	248.96	178.58	169.27	1.52	1.63	1.11	1.07	1.47

S_{obl}, V_{obl} – Surface area and volume of cones according to formula 1
S_w , V_w – Surface area and volume of cones according to cylinder model
S_s , V_s – Surface area and volume of cones according to cone model

The recalculated actual values for surface area S_{fw} and volume V_{fw}, amounted to an average 157.88 (±10.13) cm^2 and 131.20 (±11.61) cm^3, respectively. The graphical comparison of examined values (surface area and volume) is shown on Figure 4.

By using variance analysis, significant difference was found between S_w and remaining surface area, and between S_{wf} and S_s ($p = 0.013$) and S_w ($p < 0.05$). A significant difference for $p < 0.05$ was found between V_w and all other examined volume calculation models, when all volume values were compared. Significant dependence for these values was also confirmed by the Levene's test for homogeneity of variance performed for the examined calculation models. It was found that values of volume and surface area have normal distribution.

Value of k_3 indicator amounted to an average of 0.96 (±0.03). The value of volume calculated from cone model (equation 14) was smaller by almost 5% from the actual volume V_{rz}. On the other hand, k_5 indicator had an average value of 1.12 (±0.07). Surface area calculated from modified cone model (equation 13) was on average smaller by 8% from the surface area S_{obl}, recognized as actual.

4. Discussion

While comparing the results of external parameters of the examined Silver fir cones, it was noticed that they were within the range given by other authors (Barzdajn 2009). They were most similar to the parameters obtained for the Silver fir cones from Romania by Nanu (1977). The length of cones ranged from 7.0 to 19.5 cm, and the thickness ranged from 2.9 to 4.6 cm. Similar results were also given by Kočiová (1974) who described the cones from Slovakia.

By knowing the length and thickness of a cone, the surface area and volume of closed cones can be calculated. The proposed model of a polynomial of fourth-degree was used only for description of the cone's shape and for calculation of the surface area and volume of the closed cones. An attempt to apply the polynomial to cones of different parts, with the use of average values of *A, B, C, D* and *E* coefficients of equation, did not succeed because it gave much inflated results. The proposed second and third way of calculating surface area and volume of a cone with the use of cylinder or cone turned out to be more useful. The values of volume calcula-

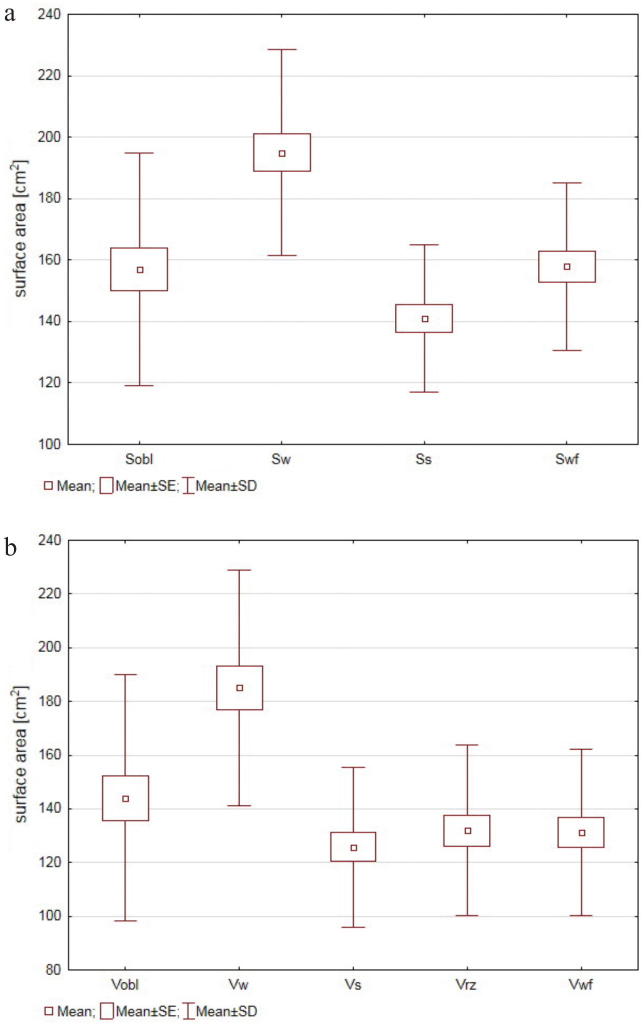

Figure 4. Comparison of mean values, standard errors and standard deviations for the test computational models: *a* – surface area, *b* – volume: S_{obl}, V_{obl} – calculated from the formula 1 and 2, S_w, V_w – calculated according to the formula on the cylinder, S_s, V_s – calculated according to the formula on a cone (13, 14), S_{wf}, V_{wf} – calculated according to the formula for the inclusion of a fixed cylinder

ted with the use of first of mentioned above entities had to be multiplied by a constant 0.709. After recalculating, the obtained values of volume were compared with the actual values of volume designed with the use of hydrometric method (V_{rz}). On an average, the ratio of the sizes equalled 1.00 (±0.03), which proves that the model was well matched. In order for the surface area of a closed cone, which was calculated with the use of formula for cylinder (S_w), to be comparable to value of surface area calculated with the use of function of polynomial of fourth-degree (S_{obl}), it should be multiplied by a constant 0.810. As a result, the proportion of calculated areas amounted to an average of 1.04 (±0.08).

A research conducted for other species, that is Scots pine and common spruce, defined a way of calculating the surface area and volume from the formula for cone (Aniszewska 2001; Gawart, Mikłaszewicz 2000). The values of surface area and the volume of Silver fir cones calculated according to this method, in comparison to surface calculated as a function of polynomial of fourth-degree, and the actual volume were smaller by 8 and 5% (k_5, k_3), respectively. For common spruce, the values of surface area varied by 5%, and values of volume by 10% (Aniszewska 2001).

The examined parameters of Silver fir cone, such as length, thickness, mass, humidity, surface area, volume and density can be used in programming thermal peeling processes in cabinet kilns in economic conditions for obtaining seeds of good quality.

5. Conclusions

1. The shape of cones of Silver fir quite accurately defines the curve, which is a polynomial of fourth-degree. However, due to vary large differences in relation to actual values of obtained coefficients for this polynomial, an average value cannot be obtained and used for the calculation of volume and surface area of any cone, despite significant dependence on length and thickness of a cone (beside *D* coefficient).

2. The formula for cylinder or cone can be a general calculating model describing surface area and volume of cones. The values of volume calculated using the formula for cylinder should be multiplied by a constant value 0.709, and in case of surface area, by the constant 0.810. However, by using the formula for cone, the description introduced should be the coefficient $\alpha = 0.3$. Result analysis showed that the surface area and volume differed only by 8 and 5% respectively, from actual values after introducing α coefficient.

Conflict of interest

The authors declare lack of potential conflicts.

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Authors' contribution

M.A. – concept , literature review , methodology , measurement, analysis of results, a statistical study , conclusions, writing , proofreading; U.B. – literature review, measurement, proofreading

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